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Scattering of Terahertz Radiation from Oriented Carbon Nanotube Films

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Abstract: We report on the use of terahertz time-domain spectroscopy to measure scattering from multi-walled carbon nanotubes aligned normal to the film plane. Measurements indicate scattering from the nanotubes is significantly stronger than for bulk metal.

OCIS codes: (300.6495) Spectroscopy, terahertz: (290.5820) Scattering measurements; (160.4236) Nanomaterials

Terahertz (THz) time-domain spectroscopy of carbon nanotubes has been used to investigate their optoelectronic properties [1-3]. These works focused on characterizing the frequency-dependent electronic and optical properties (refractive index, absorption, and conductivity) of a variety of configurations of carbon nanotubes. We present results examining the scattering of THz radiation from multi-walled carbon nanotubes oriented perpendicularly to the substrate plane. Despite the wavelength of the terahertz radiation (0.3 - 3 mm) being significantly larger that the diameters of the nanotubes, significant scattering of the incident terahertz radiation occurs. In fact, when compared to measurements performed on bulk metals, the scattering from the oriented nanotubes is significantly higher.

A commercial THz time-domain spectroscopy system with fiber-coupled photoconductive antennas is used to perform the scattering characterization. THz pulses are normally incident on the sample (0 degrees) and the scattered radiation is detected in reflection at several off-axis angles varying from 20 to 80 degrees (Fig. 1a). Wire-grid polarizers are placed in front of the transmitter and receiver antennas to insure which polarization component is incident on the samples and detected. The multi-walled carbon nanotube sample

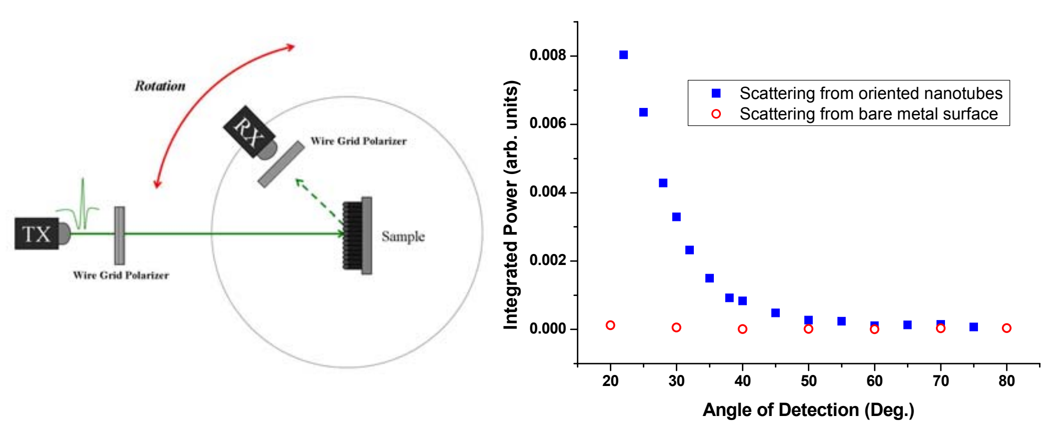

Fig. 1(a). Scattering characterization setup. (b) Scattered power versus detection angle from the carpet nanotubes and bulk metal.

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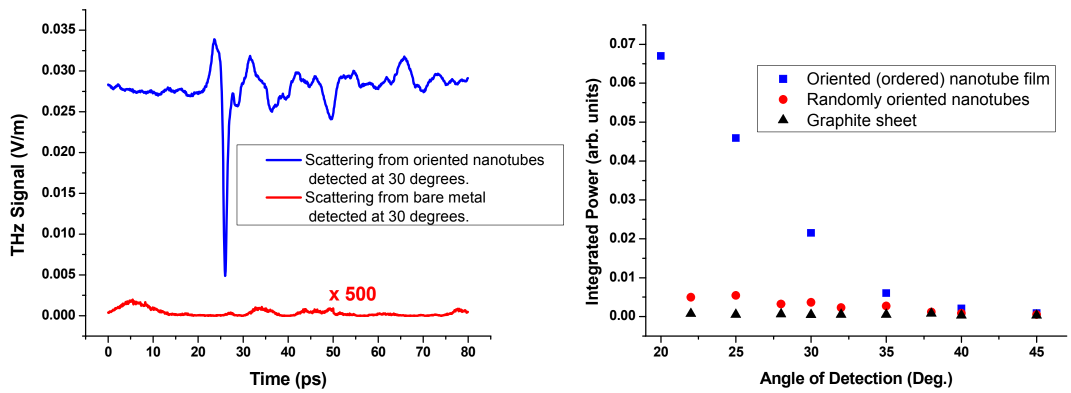

Fig. 2(a). Time-domain waveforms of the THz radiation scattered from the nanotubes and the bulk metal. (b) Scattered power versus detection angle from the carpet nanotubes and bulk metal.

was grown via chemical vapor deposition to form carpet-like films consisting of nanotubes aligned approximately parallel to one another and normal to the plane of the glass substrate [4]. The approximate density of the carbon nanotubes in the carpet film is $5x10^6$ mm^{-2}.

Fig. 1(b) shows results from time-domain measurements on multi-walled carbon nanotubes in which the THz pulses are normally incident on the sample and the scattered radiation is detected in reflection at several off-axis angles. These results are compared to radiation scattered off of a bulk metal sample (brass), indicating that the scattering is greatly enhanced in the presence of the carpet-like film of nanotubes. The THz radiation scattered by the carpet falls off exponentially with increasing detection angle and does not return to an intensity level comparable to scattering from bulk metal until 60 degrees. THz scattering is not as pronounced when the experiment is performed with nanotubes aligned along the substrate plane. Fig. 2(a) compares the time-domain waveforms at the 30 deg. detection angle when the pulses are incident on the nanotube carpet and on bulk metal. It can be seen that the THz radiation scattered off of the carpet is significantly larger than that for bulk metal. While Fig. 2(a) shows only an 80 ps long time window, actual measurements were performed over a much longer time window and no scattered radiation from the bulk metal at a magnitude comparable to that for the oriented nanotubes is present. Fig. 2b provides evidence that the oriented alignment of the nanotube carpet is critical to this scattering phenomenon. THz radiation scattered from films of randomly oriented multi-walled carbon nanotubes and a sheet of graphite are more similar in magnitude to scattering from bulk metal than from oriented nanotubes. Preliminary analysis of the data in the frequency-domain indicates that the scattering is independent of frequency.

These results are counter-intuitive as the wavelength of the THz radiation is large enough that scattering from the nanotube carpets should not differ from the bulk metal with such significance. While the conductivity of brass is not the highest as compared to other metals, the conductivity of the nanotubes is not expected to be larger than for the brass metal. In fact, measurements of the back-reflected THz pulses (A pellicle beam-splitter was added to the setup) from both the metal and nanotube carpet shows that the reflected pulse from the brass is greater. It is only at off-axis points that the scattered radiation is greater from the nanotube carpet. Further studies will explore the effects of nanotube density, polarization dependence, and the variation of the incidence angle on this interesting scattering phenomenon.

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